Electron Scattering on Bound and "Nearly Free" Neutrons

Sebastian Kuhn

Old Dominion University

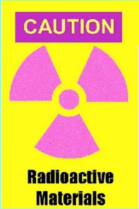
Norfolk, Virginia

Overview

- "Neutron" targets - why do we need them?
  - Form factors: separate density distribution of u, d, s quarks.
  - Unpolarized structure functions: F_{2n}/F_{2p} to extract d/u at large x; neutron resonances and duality.
  - Polarized structure functions: $A_{1n}(x\text{->}1)$ to extract $\Delta d/d$.
- Real and effective neutron targets - what are the challenges?
- The "Deeps" experiment
- The "BoNuS" experiment

Neutron Data Are Important…
…but hard to get

- Free neutrons decay in 15 minutes.
- Radioactivity!



- Zero charge makes it difficult to create a dense target
  Magnetic bottle: 10^3 - 10^4 n/cm^2 [TU München]
  Typical proton target: $4 \cdot 10^{23}$ p/cm^2 [10 cm LH]

  => Alternative Solution: Deuterons and Helium-3.
  BUT: potentially large (and not completely known) nuclear corrections: Kinematic smearing, Binding and off-shell effects, "EMC-effect", final state interactions, coherent processes, non-nucleonic components of the wave function…

What can we do?

To learn more about the structure of the neutron, we can try two approaches:

- Study modifications of the neutron structure for bound neutrons in detail, to single out the best theoretical description of binding effects.
- Use the best possible approximation for a free neutron target: a neutron that is "barely" off-shell.

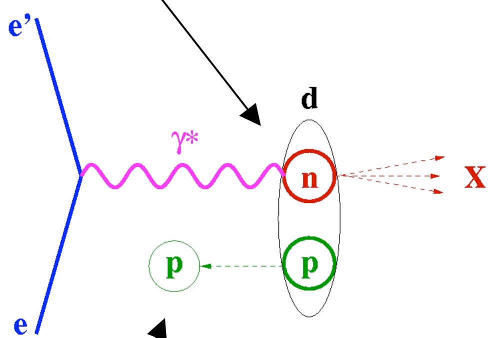
In both cases: Lepton scattering off the deuteron with simultaneous detection of a "backwards going" proton:

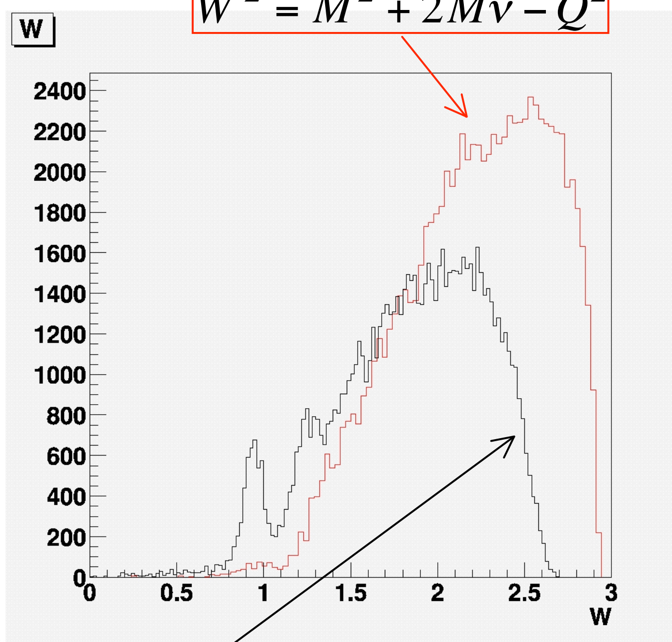
$D(e,e'p_s)X$

"Spectator Tagging"

$$W^2 = M^2 + 2M\nu - Q^2$$

$$p_n = (M_D - E_S, -\vec{p}_S); \quad \alpha_n = 2 - \alpha_S$$





$$p_S = (E_S, \vec{p}_S); \quad \alpha_S = \frac{E_S - \vec{p}_S \cdot \hat{q}}{M_D/2}$$

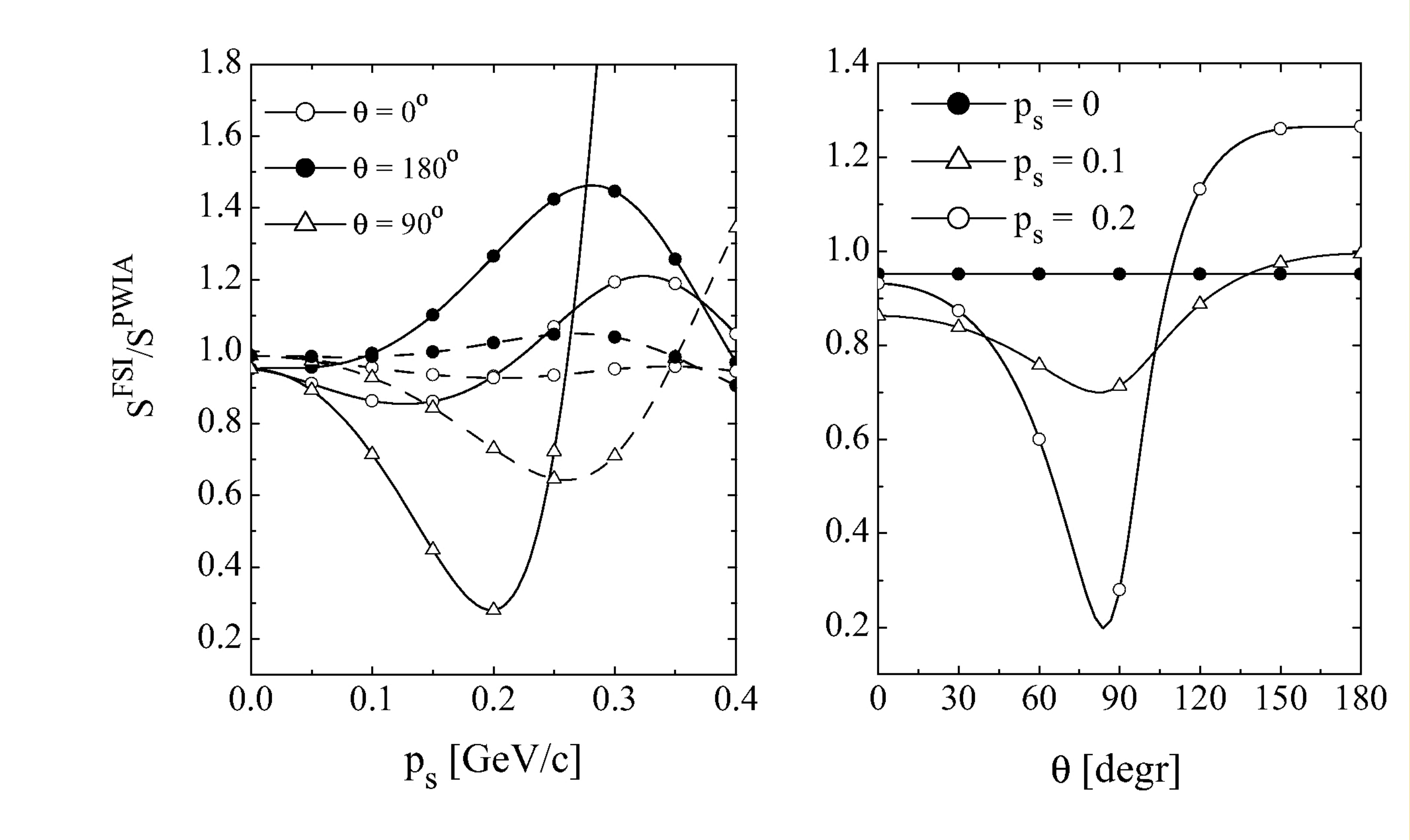
$$W^2 = (p_n + q)^2 = p_n{}^{\mu} p_{n\mu} + 2\left((M_D - E_s)\nu - \vec{p}_n \cdot \vec{q}\right) - Q^2$$

$$\approx M^{*2} + 2M\nu(2 - \alpha_S) - Q^2$$

$$x^* = \frac{Q^2}{2p_n{}^{\mu} q_{\mu}} \approx \frac{Q^2}{2M\nu(2 - \alpha_S)}$$

Deviations from the simple "spectator"picture:

1. Final State Interaction



Ciofi degli Atti and Kopeliovich, Eur. Phys. J. A17(2003)133

Deviations from the simple “spectator”picture:
2. Off-shell Effects

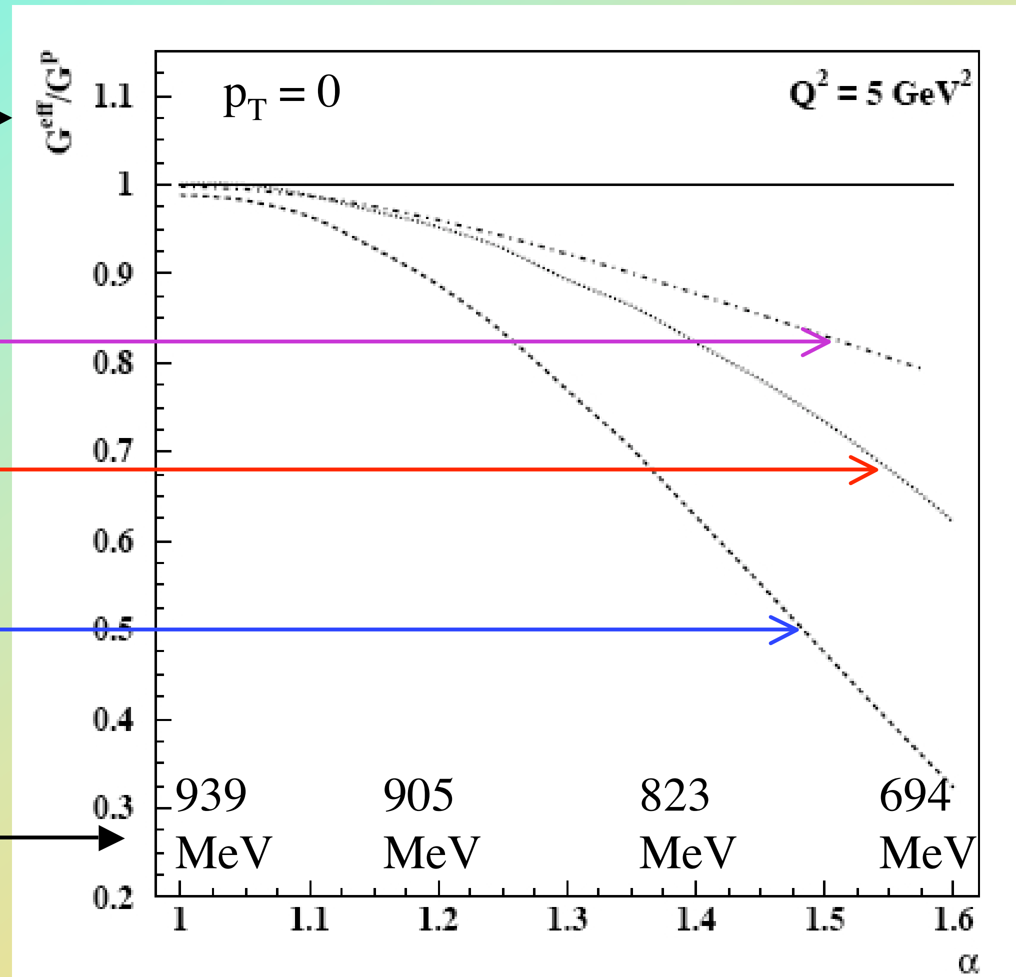
$$\frac{F_{2N}^{eff}(x=0.6,Q^2,\alpha)}{F_{2N}^{eff}(x=0.2,Q^2,\alpha)}$$

Modification of the off-shell scattering amplitude (Thomas, Melnitchouk et al.)

Color delocalization
Close et al.

Suppression of “point-like configurations”
Frankfurt, Strikman et al.

“Off-shell” mass of the nucleon M*

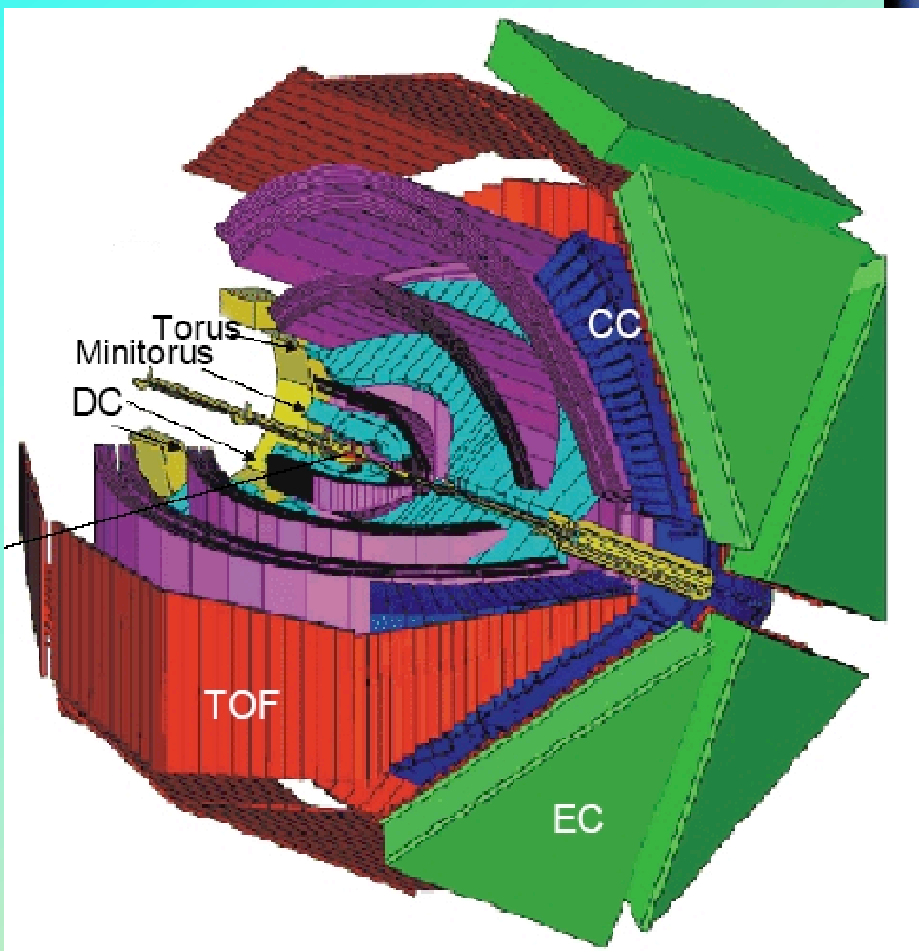


Modification of Bound Neutrons - the D(e,e'p_s) Experiment

- Experiment 94-102 at Jefferson Lab
- Run period "E6" in Hall B (CLAS)
- 5.75 GeV / 7 nA Electrons on a 5 cm long LD_2 target => $L=10^{34}/cm^2s$
- 8 calendar weeks in spring of 2002; 4.5 billion triggers
- CLAS-Collaboration and 2 Ph.D. students:
  Dr. Alexei Klimenko and
  Cornel Butuceanu

CEBAF Large Acceptance Spectrometer

Schematic Diagram



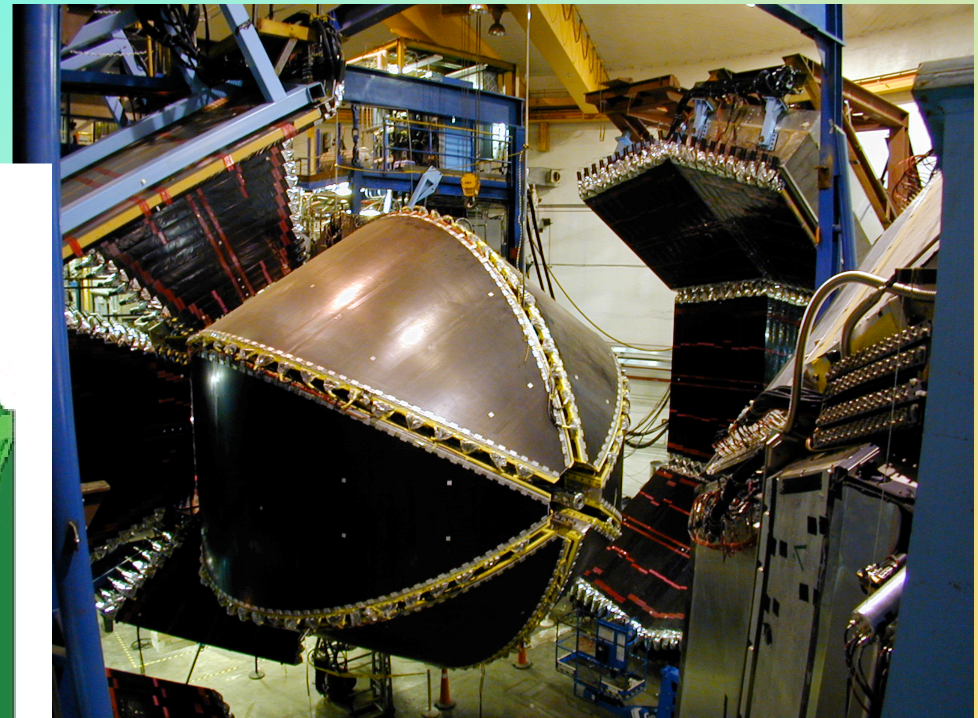
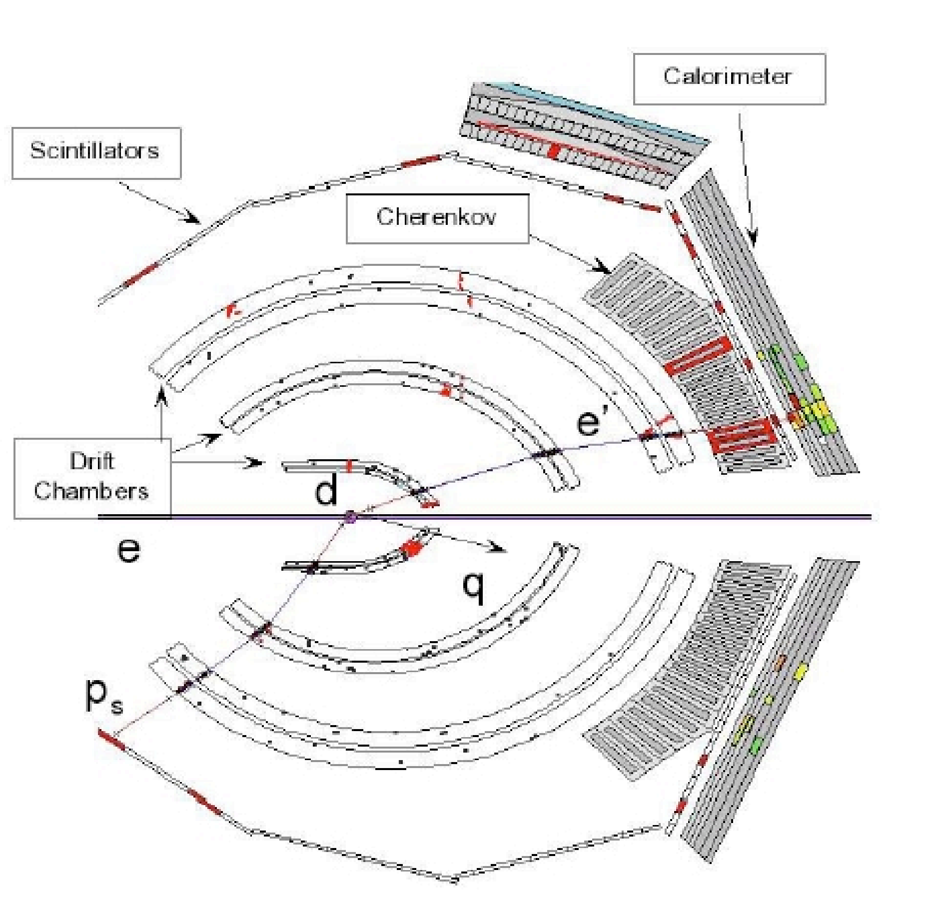
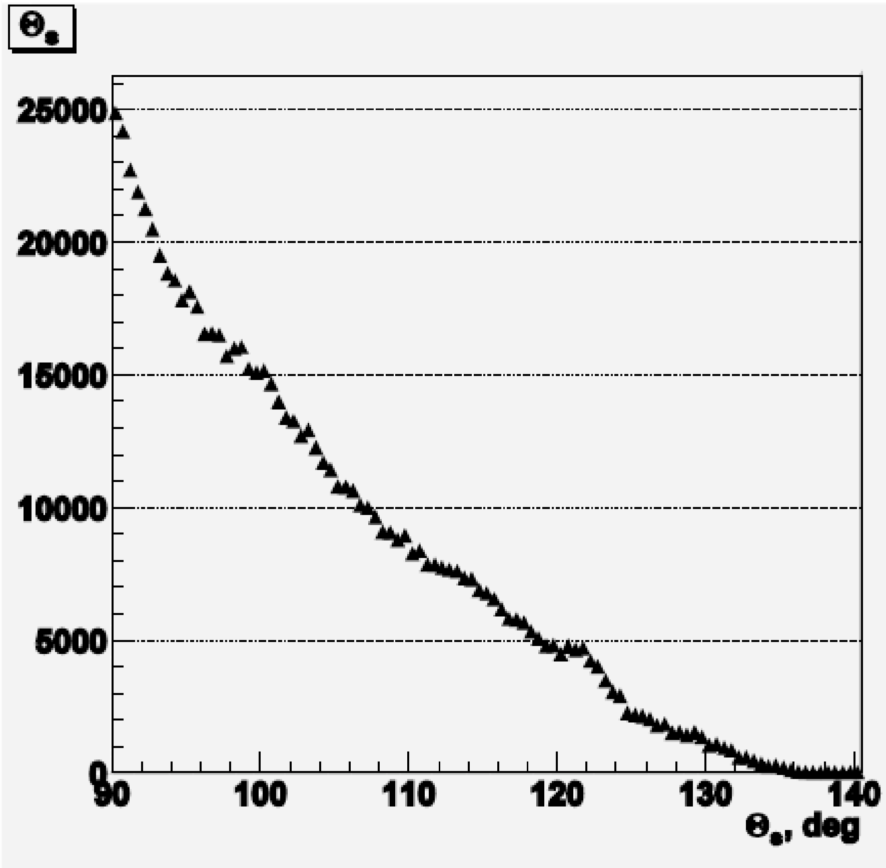


Photo of Hall B - CLAS has been opened up for service work

Experimental Details

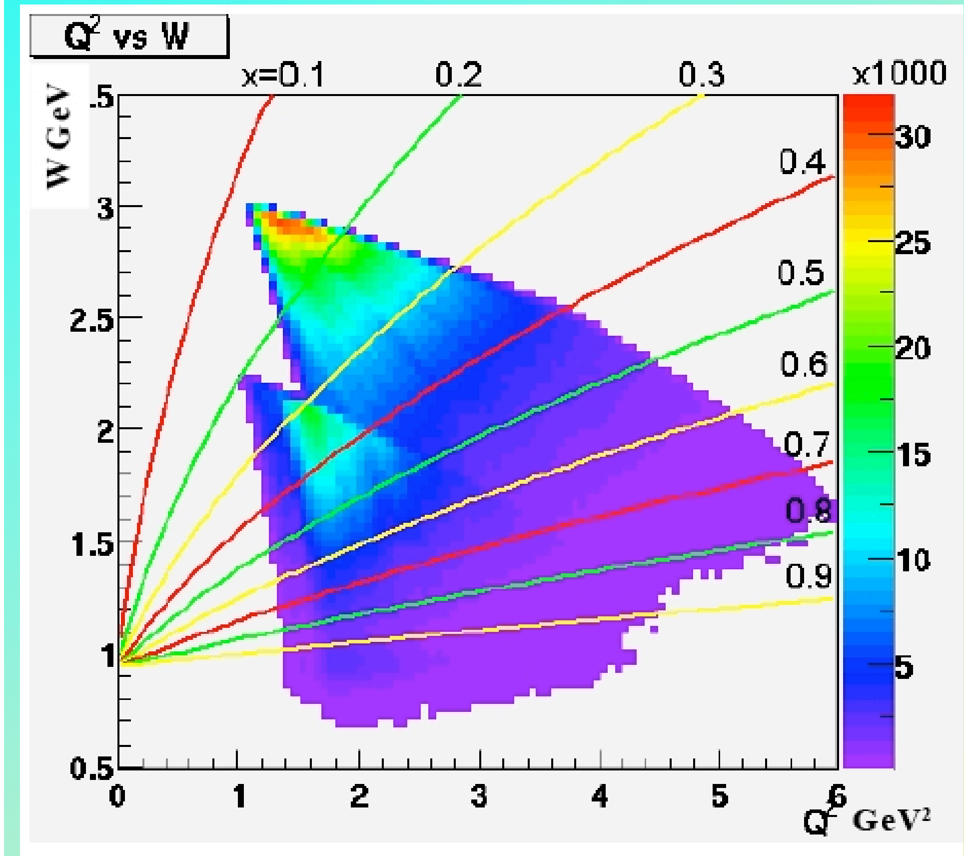


A typical event

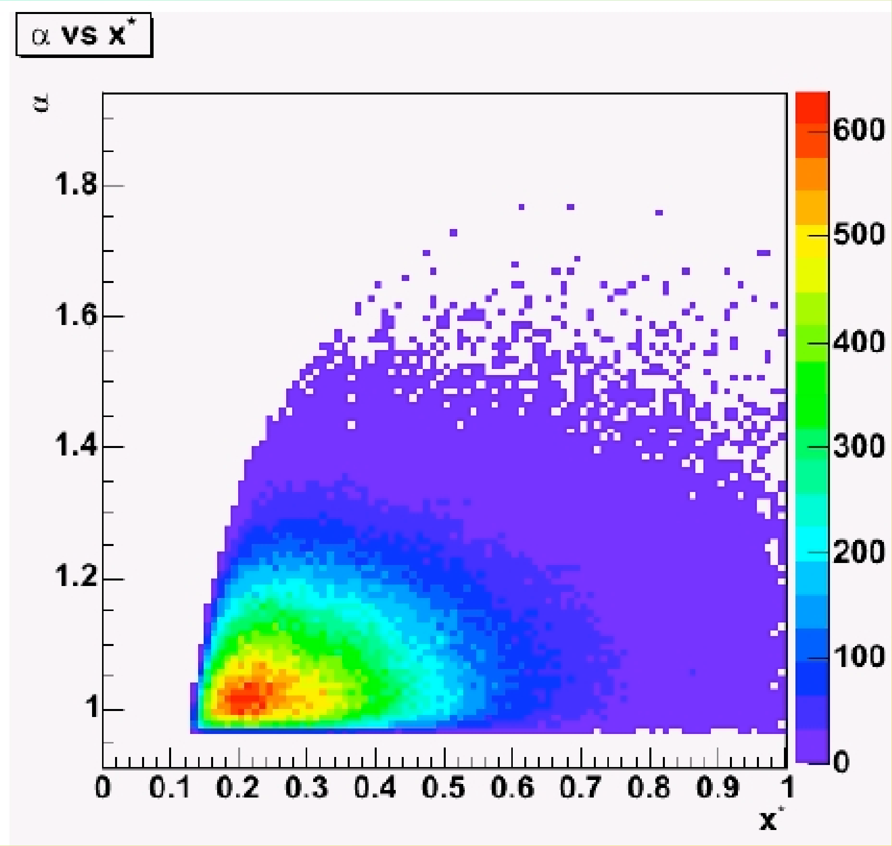


Acceptance for protons in the backward hemisphere

Kinematic Acceptance



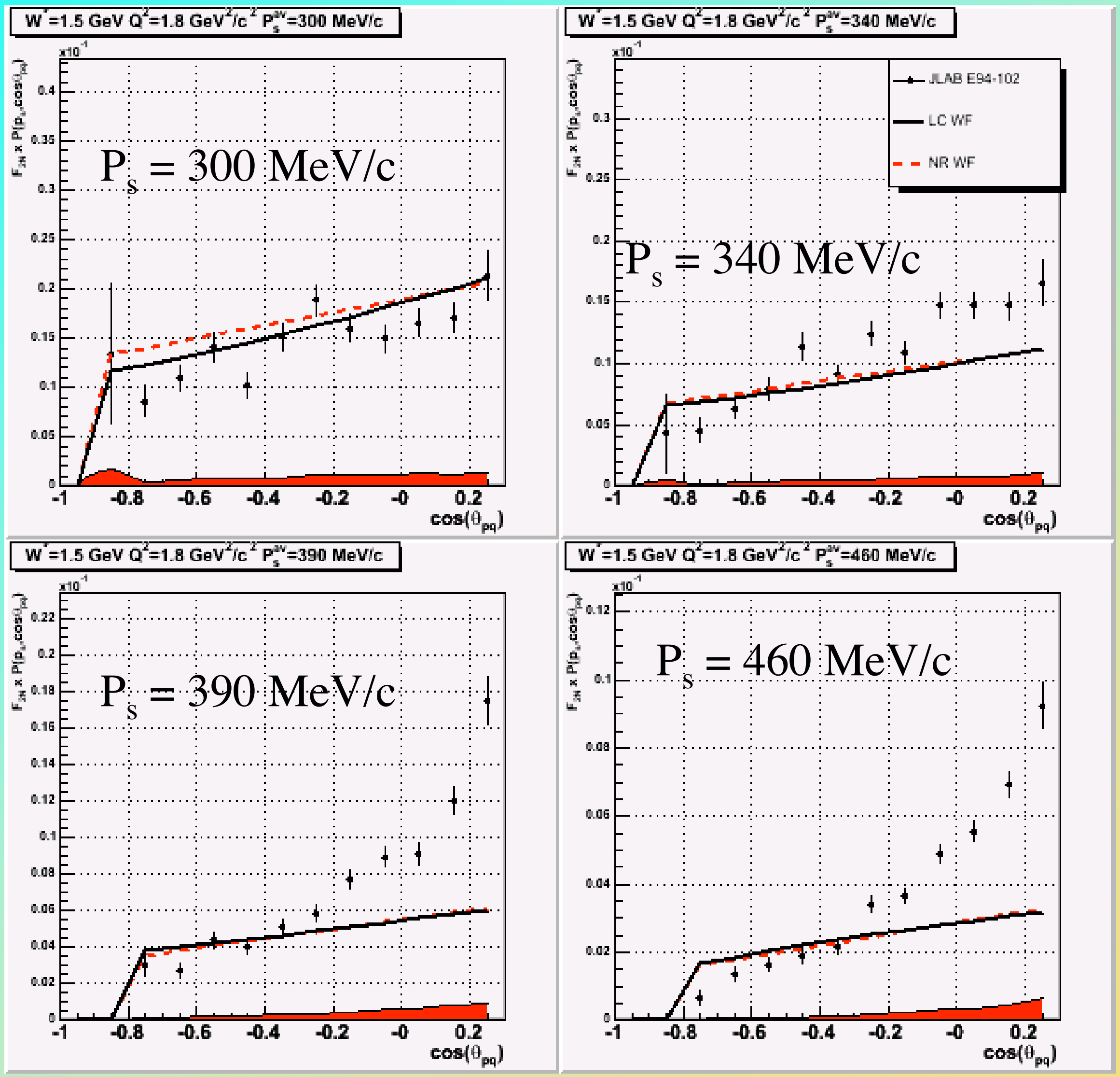
Final state mass *vs*. (momentum transfer)^2



"light cone"-variable α *vs*. Björken-x

Results: Angular Distribution (W = 1.5 GeV)

$P(p,\theta_{pq})*F_{2n}(x^*,Q^2)$



Cosine of the angle between proton and momentum transfer

Vertical Axis: cross section divided by kinematic factors => $P(p,\theta_{pq})*F_{2n}(x^*,Q^2)$

Unobserved final state in the mass range of the S_{11}/D_{13} - resonances (1.5 GeV ± 0.125 GeV)

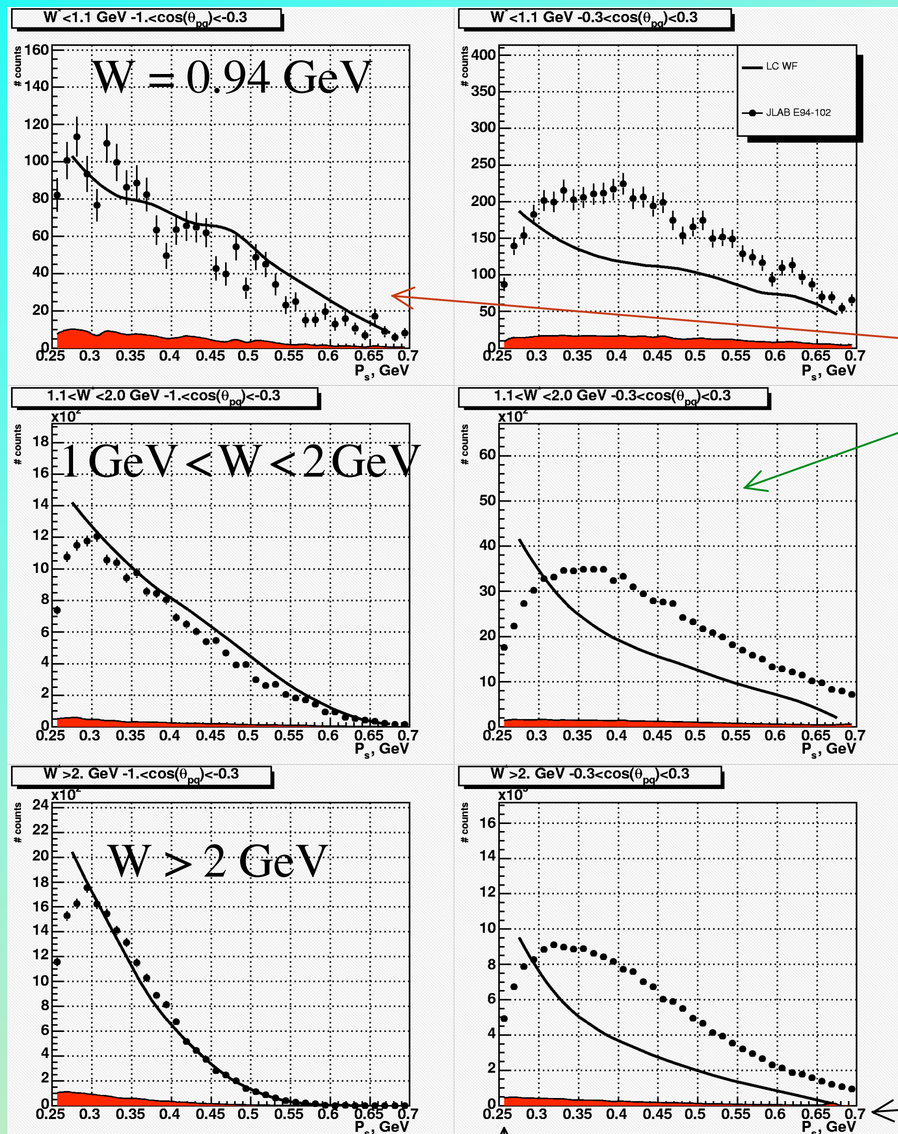
$Q^2 = 1.8\ GeV^2$

Different momenta of the detected protons

Lines: PWIA model with “light cone” or non-relativistic wave function for deuterium

Results: Momentum Distribution

Events



P_s

Vertical axis: Number of events

Horizontal axis: Proton momenta from 250 to 700 MeV/c

Left: Angular range > 107.5^{O}

Right: Angular range 72.5^{O} - 107.5^{O}

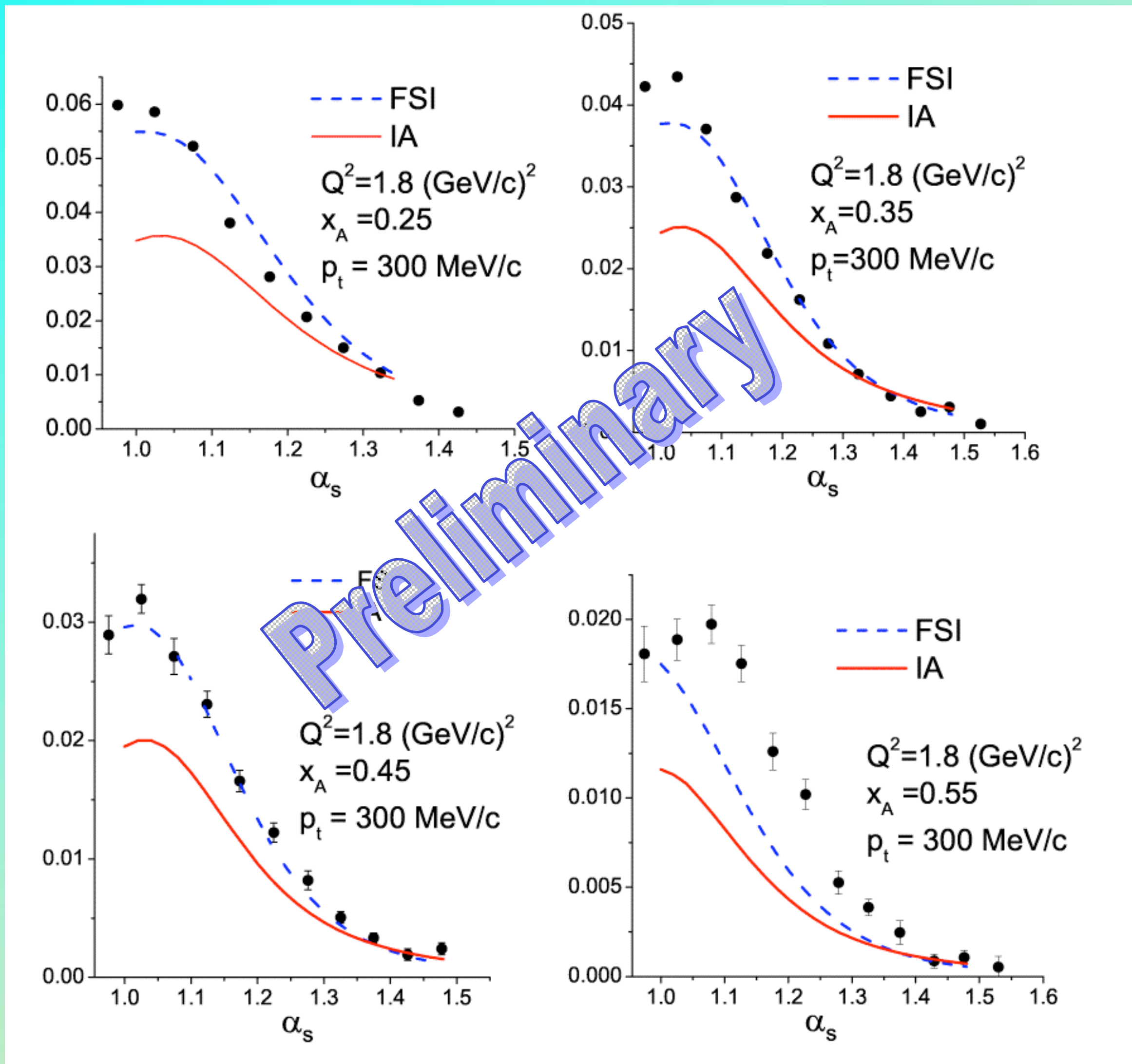
3 different ranges in the final state mass W of the unobserved struck neutrons

PWIA model with “light cone”-wave function for deuterium

700 MeV/c

250 MeV/c

Results: Dependence on α_s and x^*



Vertical axis: cross section divided by kinematic factors $= S^{DWIA}(\alpha,p_T)*F_{2n}(x^*,Q^2)$

4 different values for x^*

Calculation by C. Ciofi degli Atti et al.

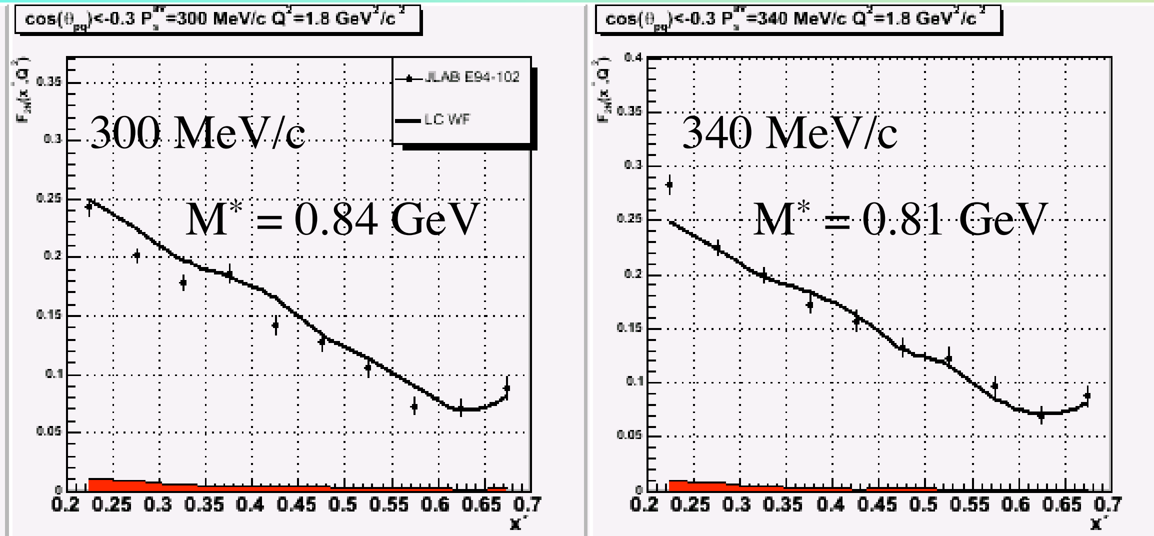
Results: x^* dependence

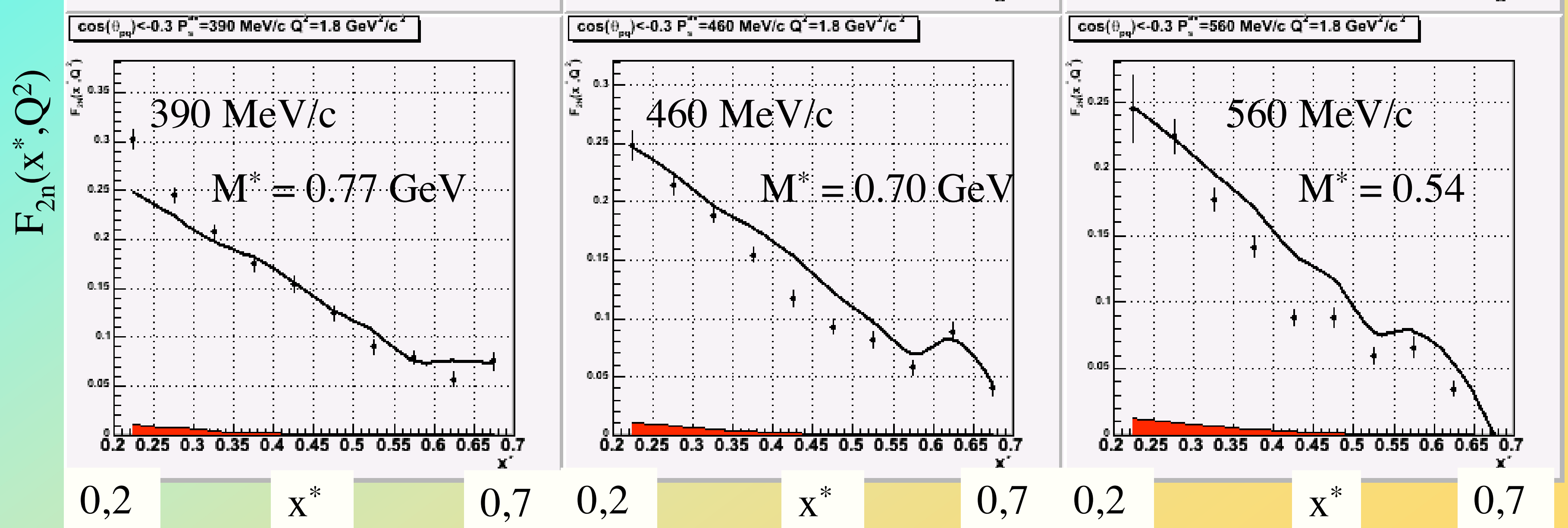
$Q^2 = 1.8$ GeV^2

Proton angles $> 107.5^{O}$

Several different proton momenta

Vertical axis: structure function $F_{2n}(x^*,Q^2)$



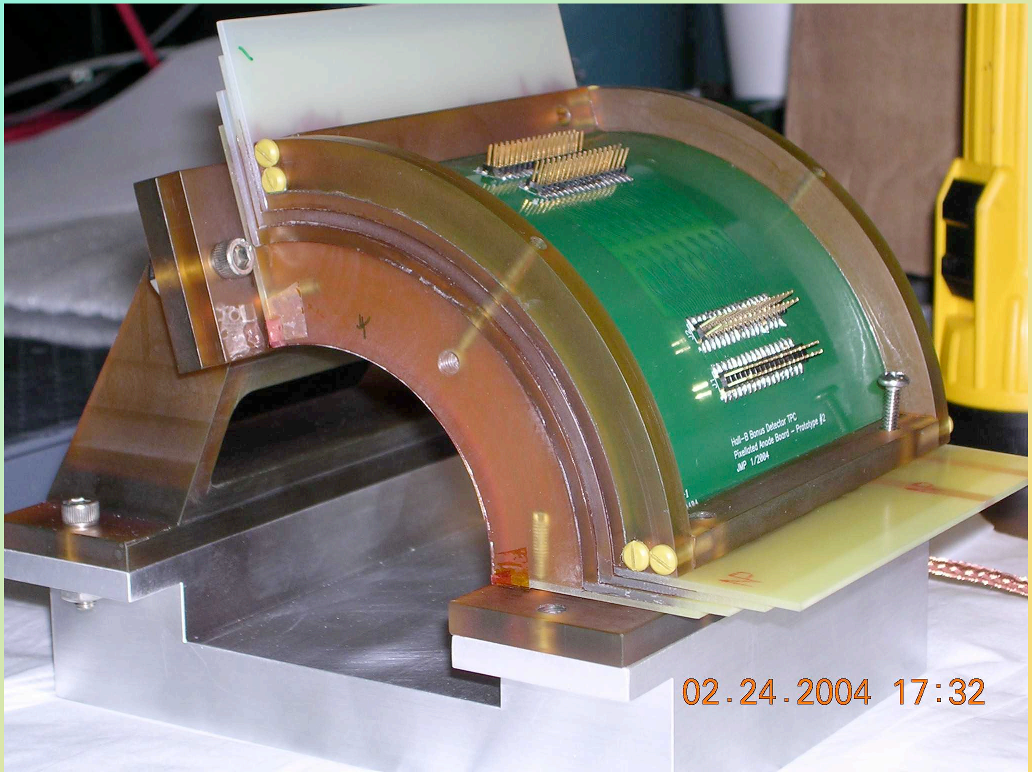


Results from "D(e,e'p_s)"

- Light cone (as well as "non-relativistic") wave function describes the momentum distribution of nucleons in deuterium rather well.
- Final state interactions play an important role, especially for sideways angles (relative to **q**) and large proton momenta. They are more pronounced for large final state mass W or small Bjorken x.
- For large "spectator" momenta (neutron is far "off-shell") we see a reduction of the structure function F_{2n} compared to that for a free neutron.

Inclusive Scattering off a “free” Neutron - the BoNuS* Experiment

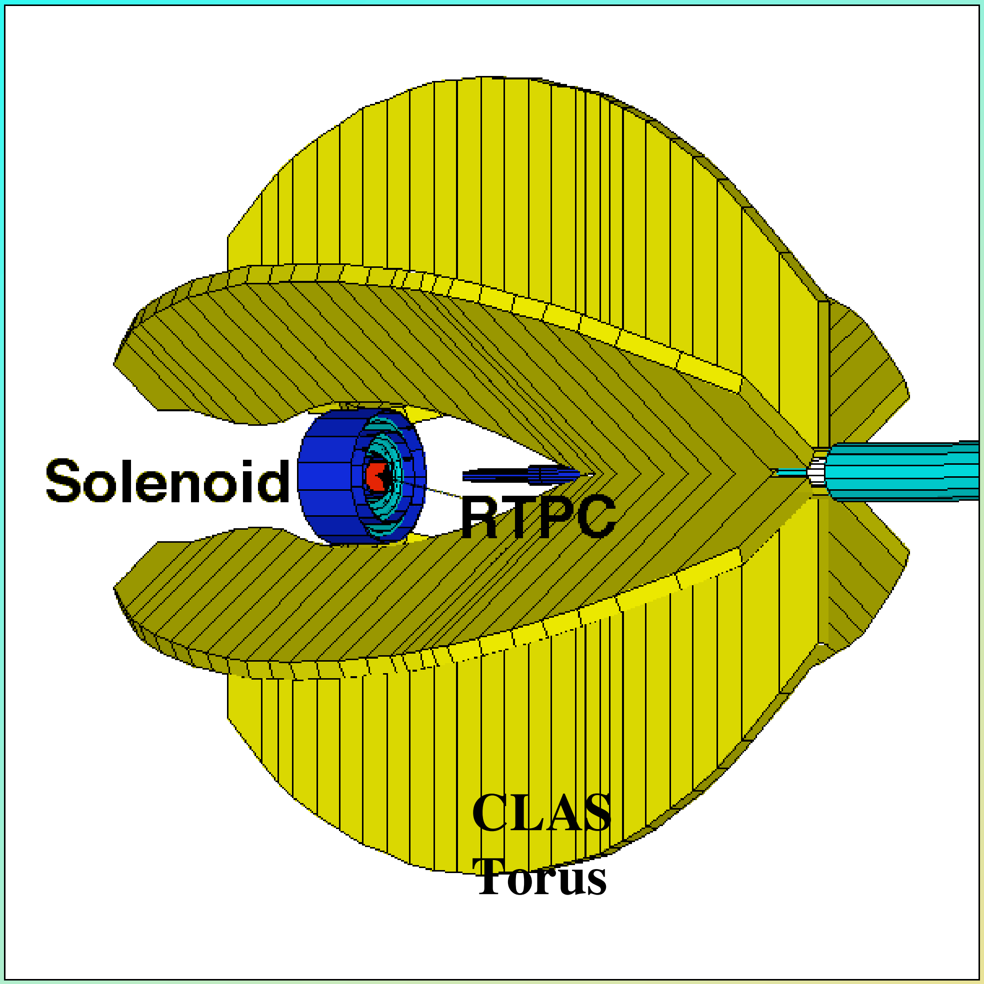
- Experiment 03-012 at Jefferson Lab in Hall B (CLAS)
- 4 and 6 GeV / 200 nA electrons impinging on a 10 cm long D_2 gas target (7 atm) => $L = 0.4 \cdot 10^{34}/\mathrm{cm}^2\mathrm{s}$
- PAC-approved for 2 calendar months of running (2005/6)
- Old Domininon Univ., Jefferson Lab, Hampton Univ., William & Mary, James Madison Univ., and the CLAS collaboration

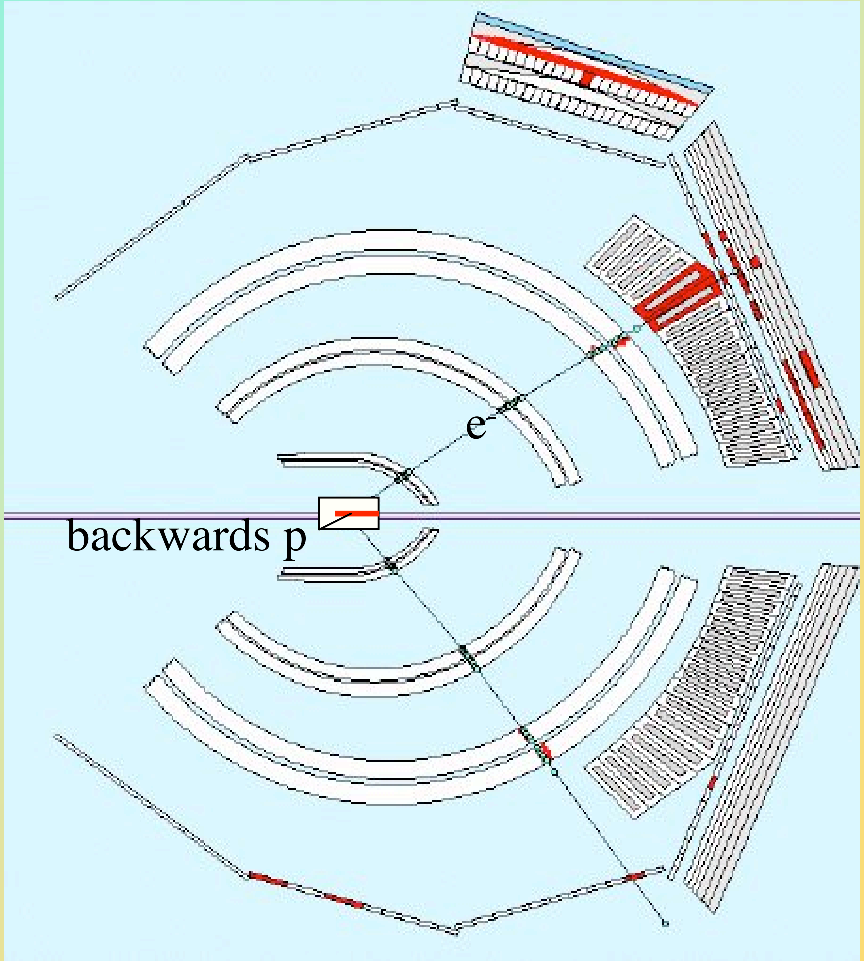


Radial TPC Prototype

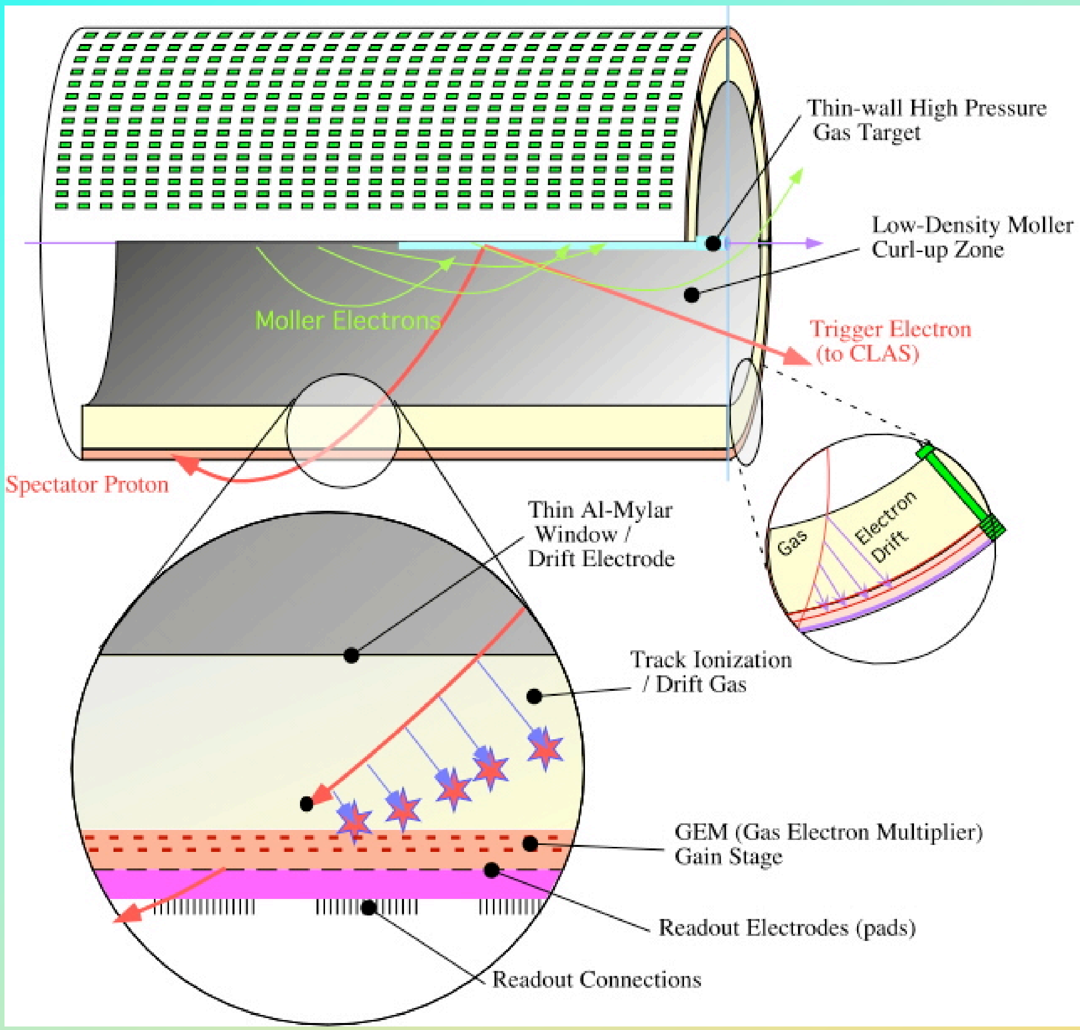
* BoNuS = **B**arely **o**ff-shell **Nu**cleon **S**cattering

BoNuS - Experimental Setup



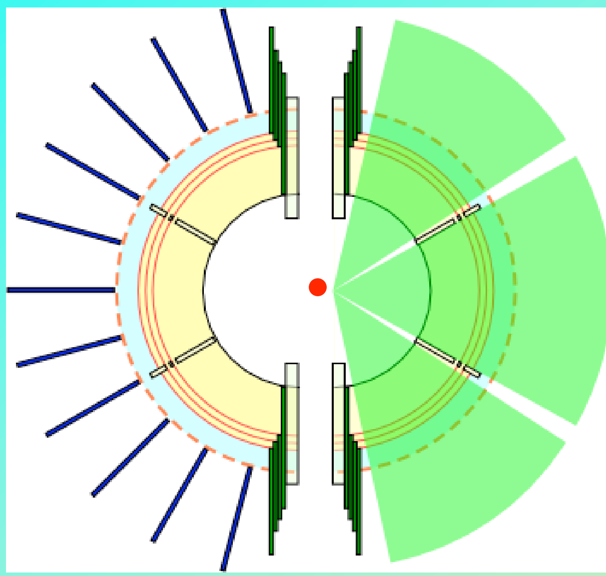


Target-detector system for slow protons

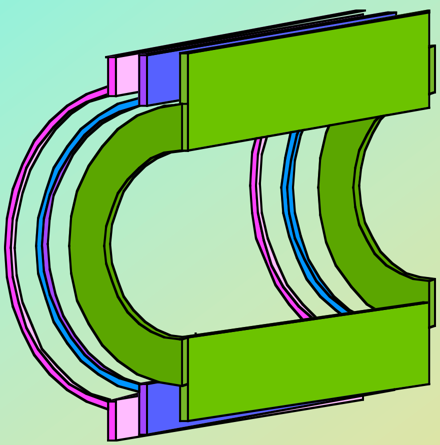


- Thin-walled gas target (7 atm., room temperature)
- **R**adial **T**ime **P**rojection **C**hamber (RTPC) with **G**aseous **E**lectron **M**ultipliers (GEMs)
- 2 Tesla longitudinal magnetic field (to suppress Möller electrons and to measure momentum)
- 3-dimensional readout of position and energy loss ("pads")

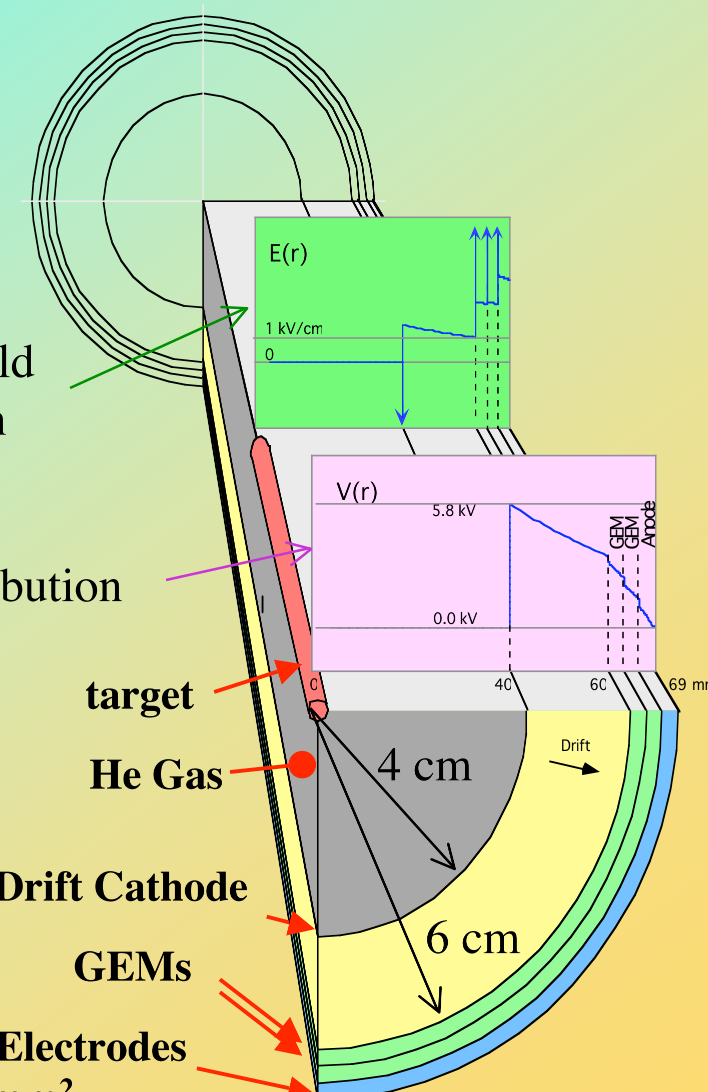
RTPC - Concept



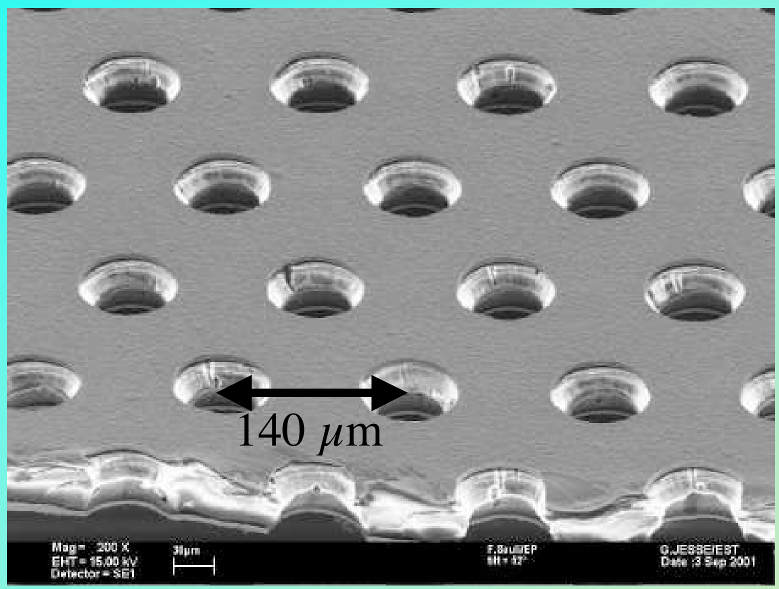
Cross sectional view

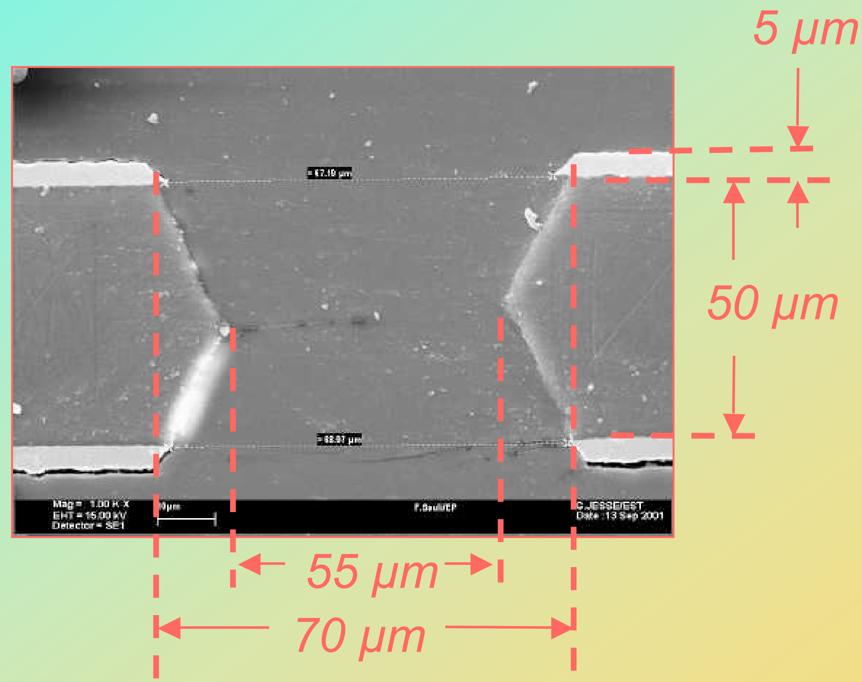


Foil supports

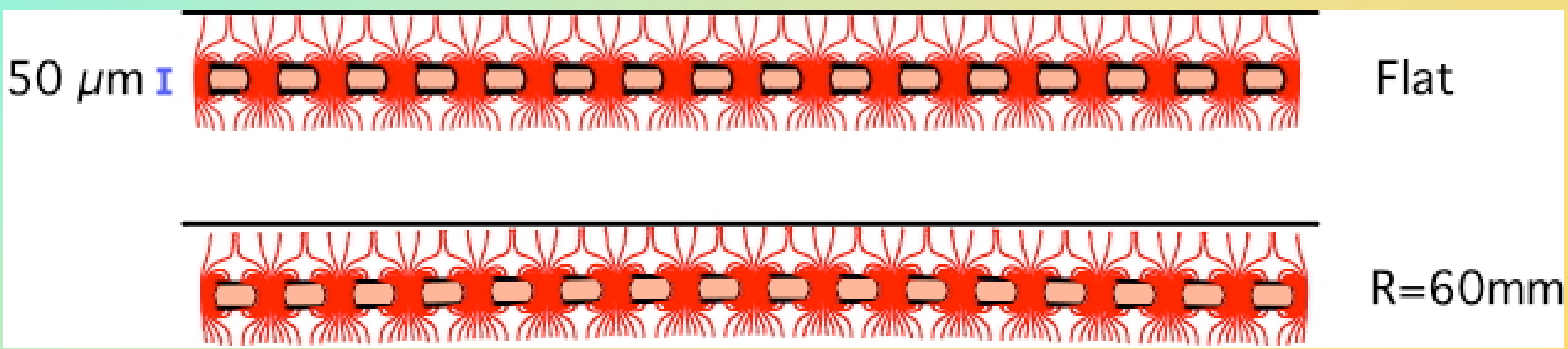


RTPC - GEMs



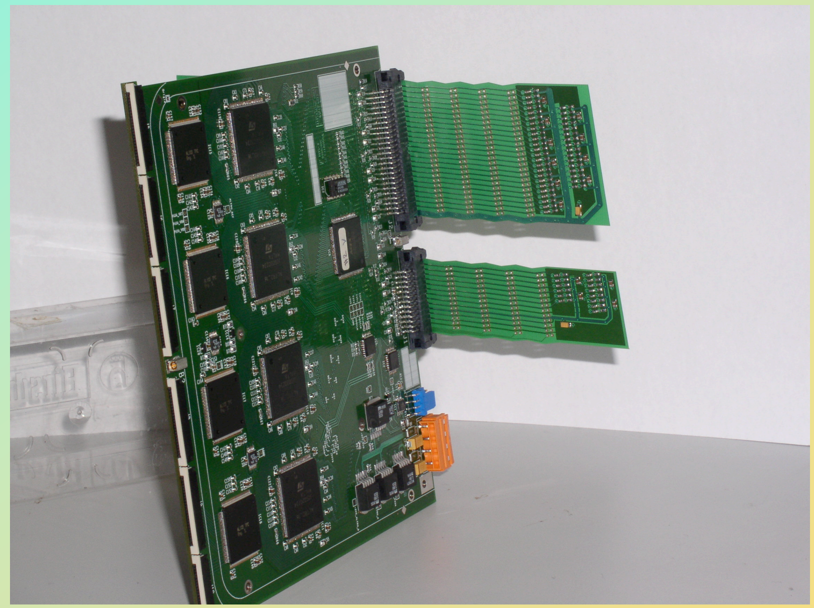


300-500 V, Gain 100-200



RTPC - Data Acquisition

- Alice TPC electronics (CERN) with Altro Chip
- 16 channels, 10 bit ADC with up to 25 MHz data rate
- 3-dimensional track reconstruction (using drift time information and 2 -dimensional location of readout pads)



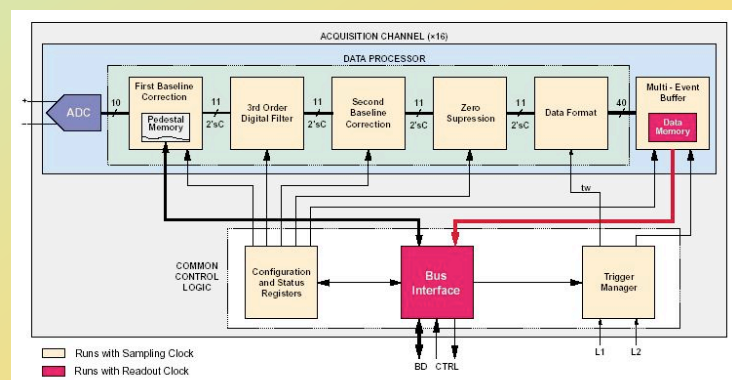
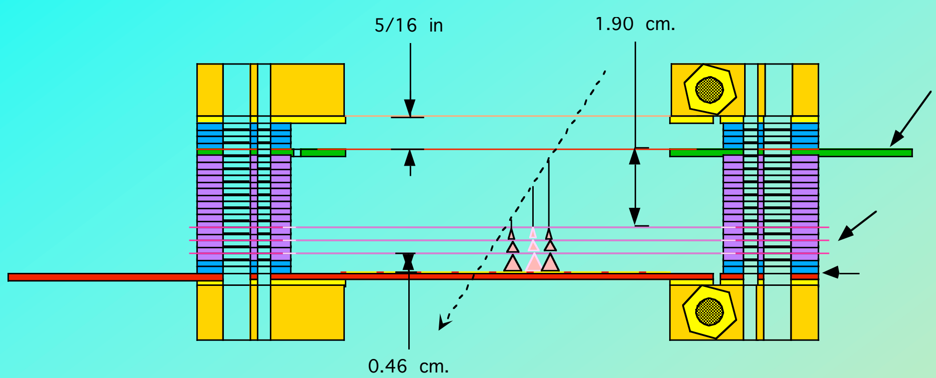
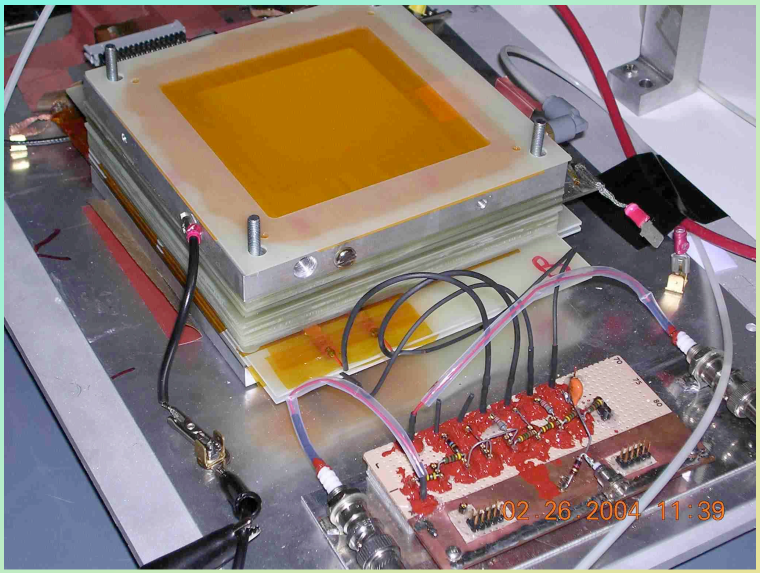
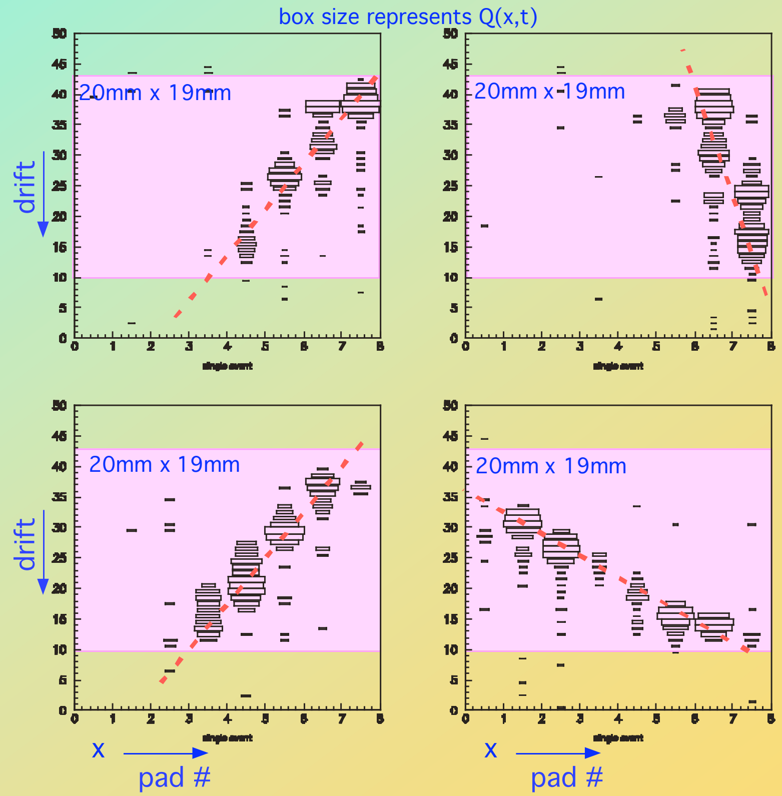


Figure 1.1. ALTRO Processing Chain

RTPC - 1^{st} Prototype

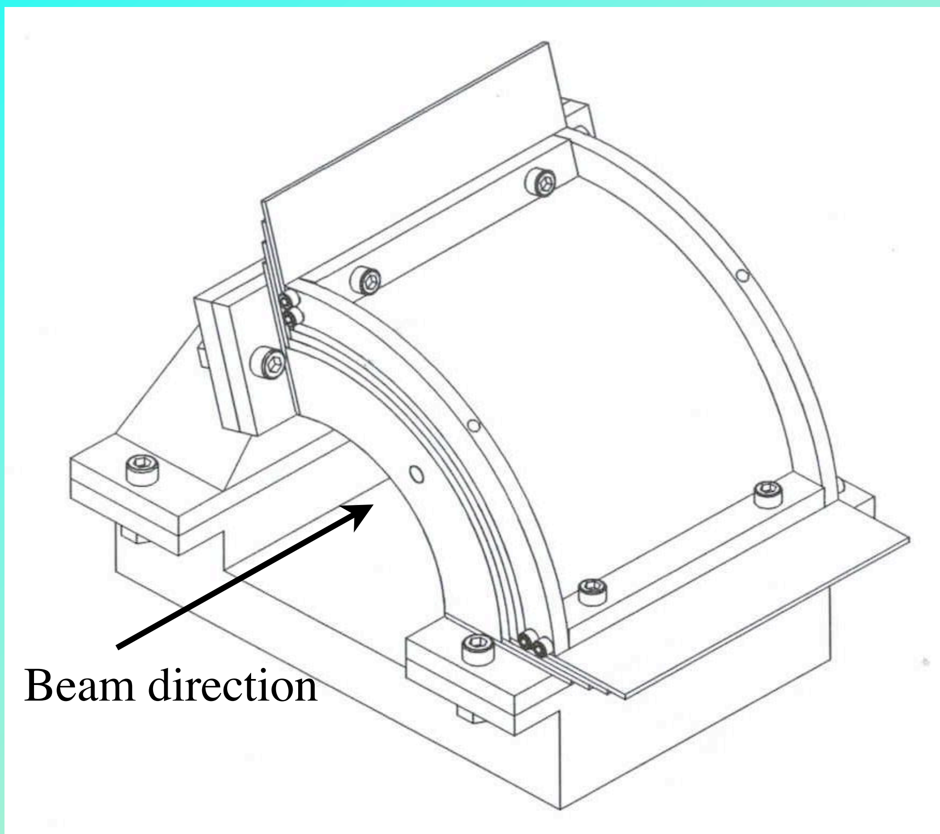


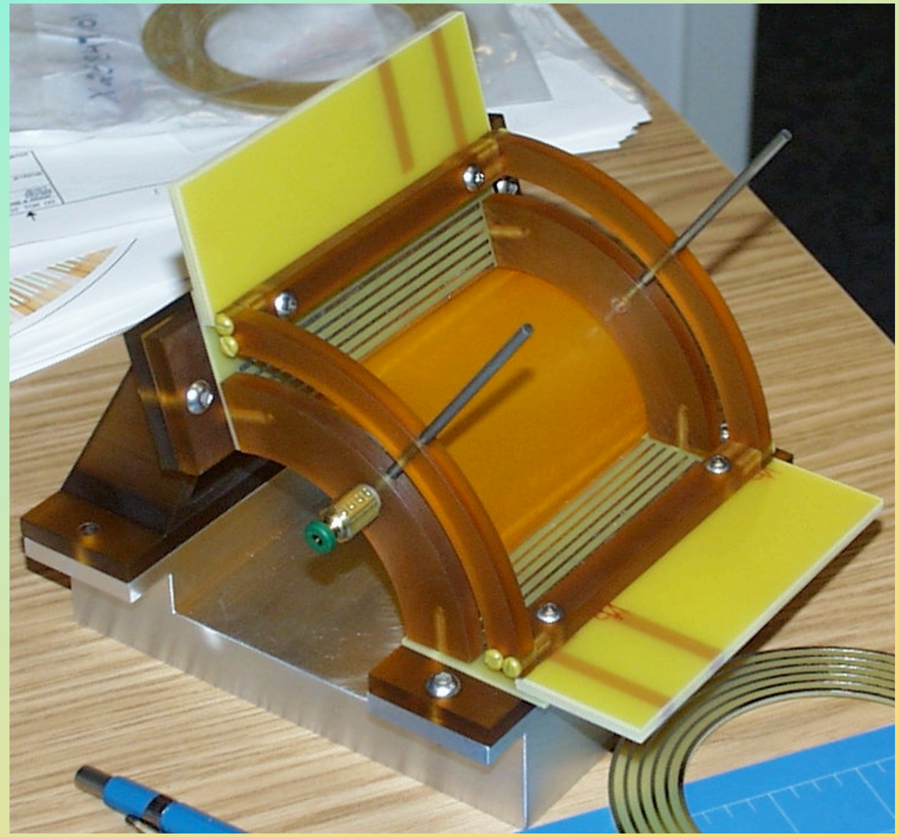




Tracks from a test run at Triangle Universities Nuclear Lab (TUNL) with 100 MeV/c protons

RTPC - 2nd Prototype

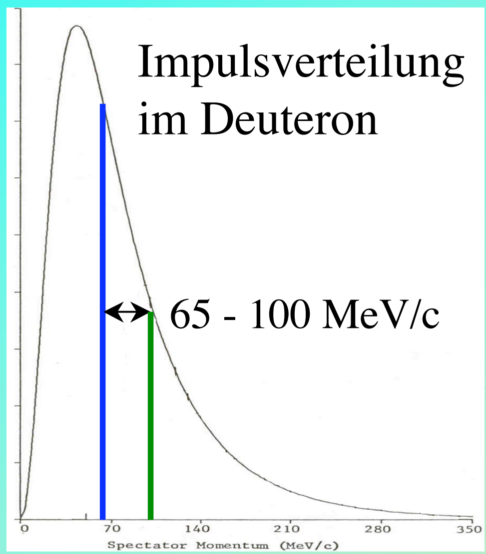


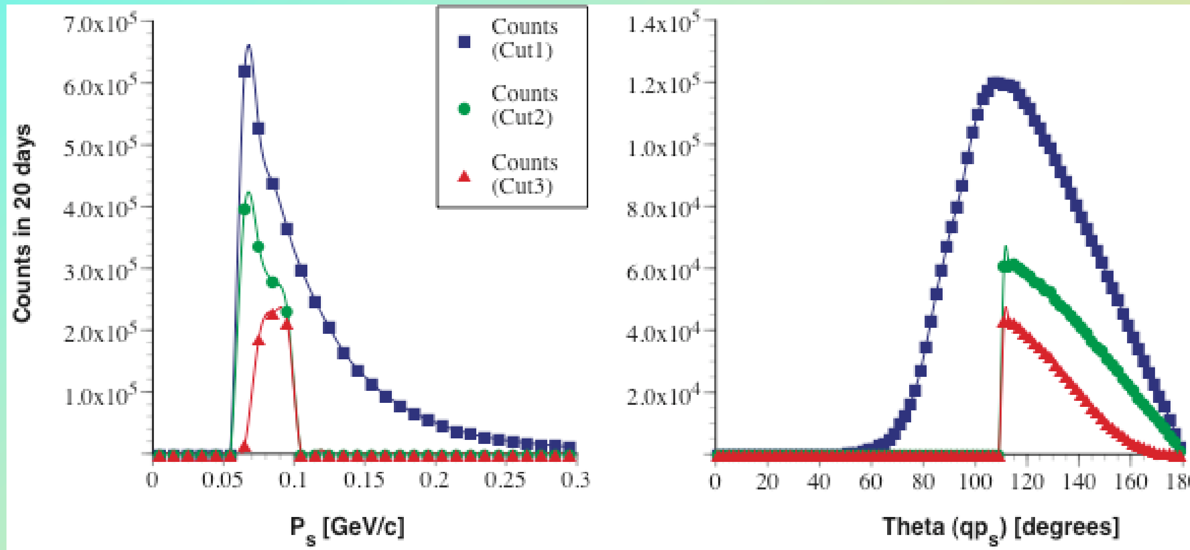


Scale 1:1, 1/8 of the final RTPC (1/2 length, 1/4 of 360^{o})

Tested at TUNL, planned engineering run with CLAS

Acceptance for Protons





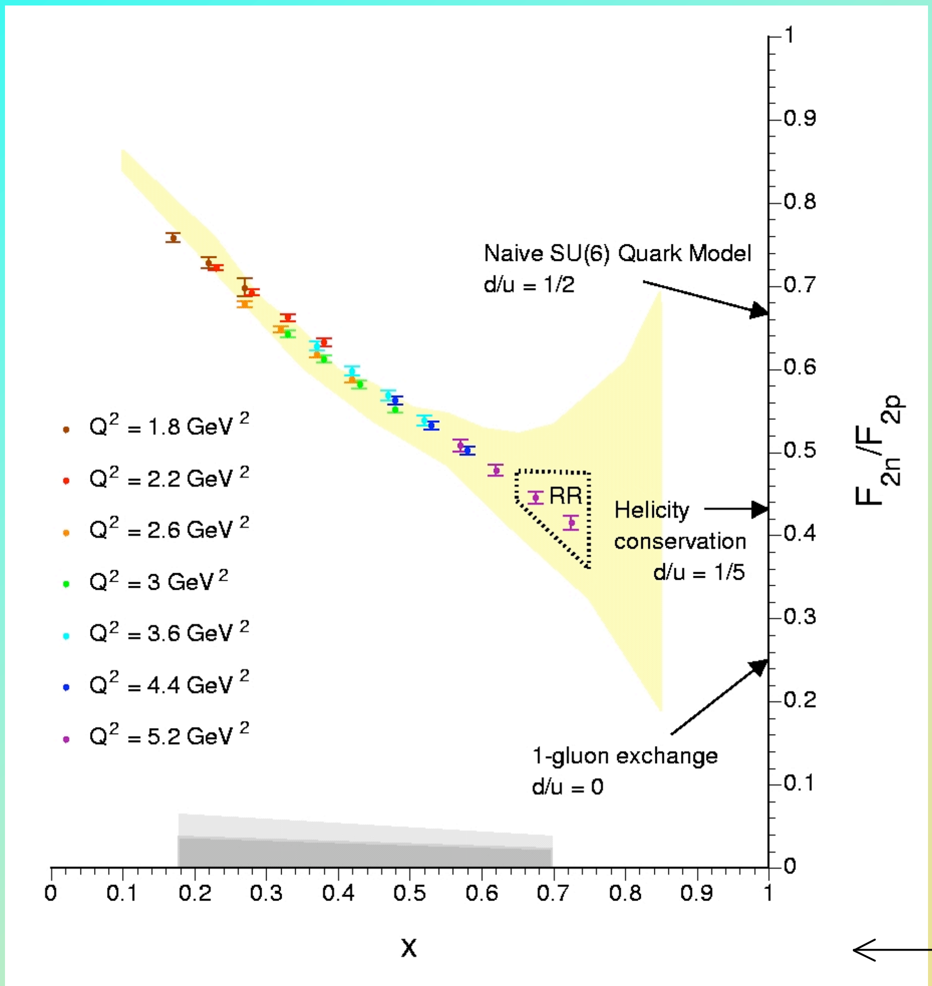
6 GeV electron beam, 20 “ideal” days -> registered “events”

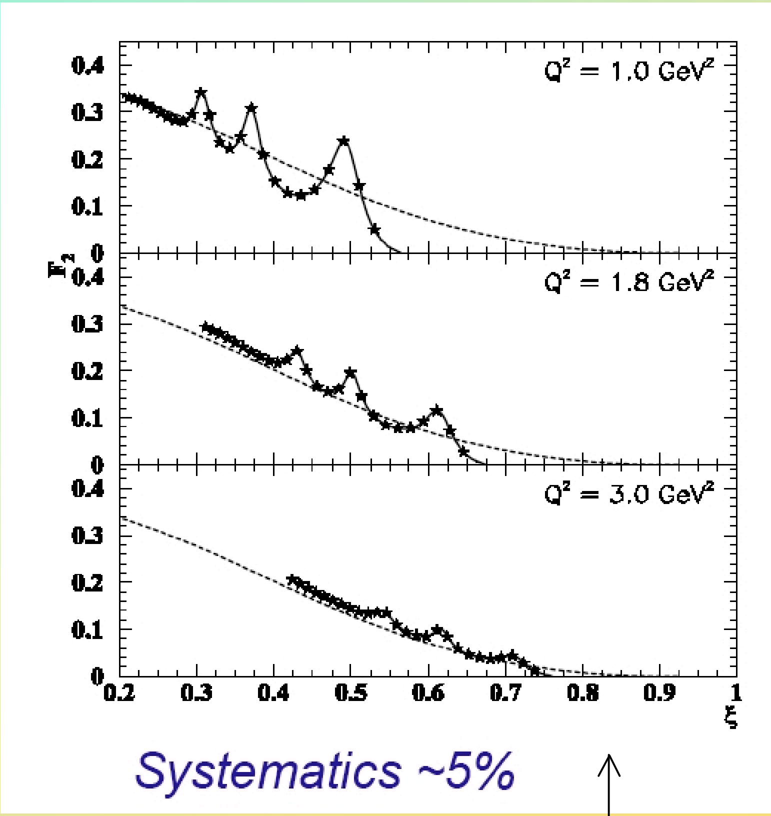
Scattered electron within CLAS fiducial cuts, proton above 60 MeV/c und 90^o

“VIPs”: p(proton) < 100 MeV/c, $\theta_{pq} > 110^o$

Proton reconstructed by the RTPC

Expected Data



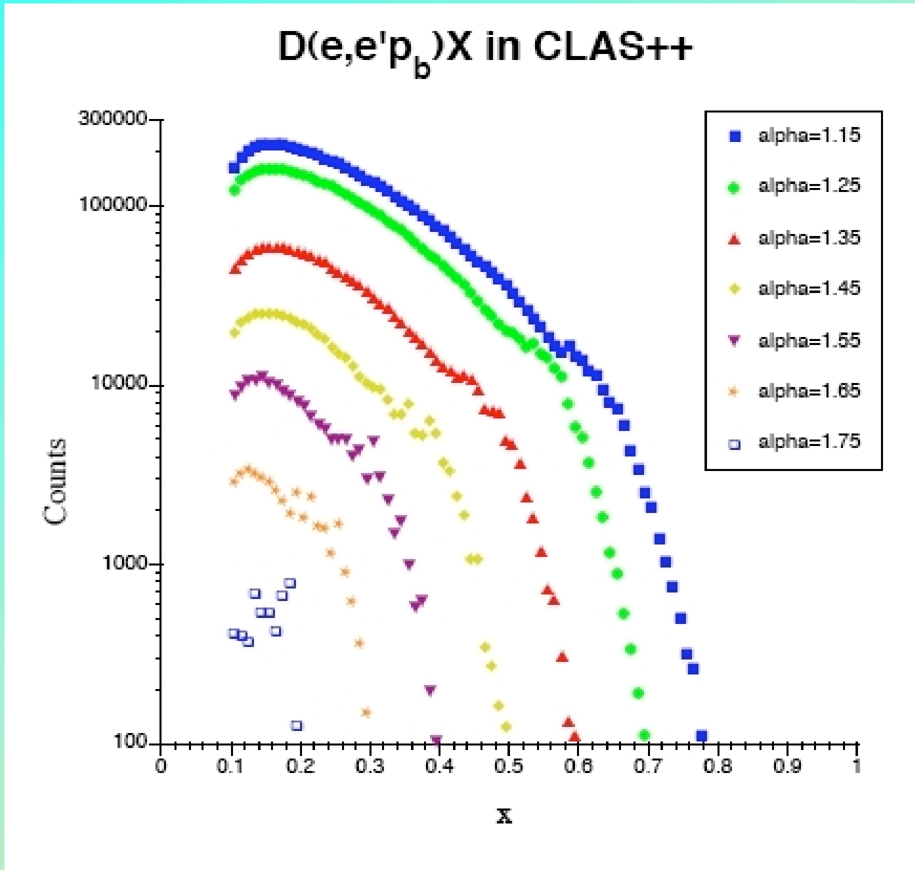


d/u

Duality

The Future - 11 GeV

D(e,e'p$_s$)



BoNuS